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Memo

Date: *Sept. 24, 2014*

To: *RSC, D. Phillips, A. Pendzick, H. Huang, C. Gardner*
Cc: *D. Paquette, R. Lee*

From: *D. Beavis*

Subject: *Soil Activation at Booster E7*

Minor update in table III and description was made on Sept. 30.

This note will provide some comments and calculations to supplement those provided at the RSC meeting[1] of August 11, 2014. A draft was provided before the Sept. 11, 2014 meeting . This noted has been updated and corrected since the draft and issues related to the RSC meeting are included.

The last meeting requested some updated information. The following has been provided:

1. The number of proton lost at E7 while the soil samples were in during run13 was $3.57*10^{16}$ protons. This is upper limit expected to be accurate to a factor of two.
2. The number of protons that are expected to be scrapped in run15 is $2.6*10^{18}$ protons. This is calculated using $8*10^{11}$ protons per 4 second cycle for five months. The loss occurs at approximately 800 MeV. No down time is included in the total beam loss.
3. K. Yip provided a new calculation[2] for the beam striking the front of an E7 magnet.
4. The soil samples were spaced 10 feet apart at beam height. The middle sample was about two feet downstream of the upstream E7 dipole iron.

The committee could not reach consensus on making a recommendation. I will use the methods that I have suggested[3] for estimating the production of ^{3}H and ^{22}Na in the soil shield and determining the size of the E7 soil cap.

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[1] Minutes of the RSC meeting of August 11, 2014; http://www.c-ad.bnl.gov/esfd/RSC/Minutes/08_11_14Minutes.pdf
[2] K. Yip, “Monte Carlo Simulation Related to Soil Activation at Booster E7”, Aug. 14, 2014; http://www.c-ad.bnl.gov/esfd/RSC/Memos/E7%20Cap.pdf
[3] D. Beavis,”Soil Activation and the BNL Subject Area”, Sept. 9, 2014; http://www.c-ad.bnl.gov/esfd/RSC/Memos/Soil_9_09_14.pdf

The soil samples that were placed in the Booster ring during initial beam scraping at E7 during run12 provided the following empirical data for ^{22}Na production in BNL soil. The total beam lost at E7 has been estimated as $3.57*10^{16}$ protons at a beam energy of 800 MeV. The beam loss is expected to be an upper limit but accurate to a factor of two better. The samples were located on the outside of the Booster ring at beam height. The locations and measured activities were:

Table I: FY13 Soil Sample Results for E7 Scrapping

Location[4]	**^{22}Na pCi/gm**	**Leachable[5] ^{22}Na pCi/cc**	**Scaled $2.6*10^{18}$/yr Leachable ^{22}Na pCi/cc**
240 cm Upstream of E7 dipole	0.023	0.003	0.22
60 cm Downstream of E7 dipole	**0.164**	**0.022**	**1.6**
360 cm downstream of E7 dipole	0.05	0.0068	0.49

Only the soil sample that is 60 cm downstream of the E7 dipole front surface is above the minimum detectable level for the analytical analysis company. The 1.6 pCi/cc will have an effective column height of 207 cm and will be flushed with 55 cc of water which results with water at the bottom of the column with a yearly average ^{22}Na concentration of 6000 pCi/liter. This is well above the DWS for Sodium 22, which is 400pCi/liter. If we use the conversion factor of one ^{3}H atom per ^{22}Na atom, convert for the different half-life, and use 100% ^{3}H as leachable then we obtain an yearly average ^{3}H concentration of 17,000 pCi/liter. This result is just under the Drinking water standard for tritium and well above the BNL action limit of 1000 pCi/liter. If the old ^{22}Na/^{3}H ratio and column height were to be used essentially the same result for this particular geometry would be obtained for tritium.

After the RSC meeting of August 11, 2014 a better estimate of the protons lost at E7 during run12 was provided. In that meeting it was reported that using the old technique that the ^{22}Na production was 26 times higher when estimated by MCNPX compared to the soil sample. After the adjustment for the lower total of lost protons the MCNPX result of K. Yip is 10 times higher than the soil sample (using the old conversion technique). Initial estimates using MCNPX by D. Beavis at 10cm into the soil are 3-4 times higher than the soil sample for the ^{22}Na production. It is not clear if the difference between calculations and measurements[6] are related to the cross sections used, the technique of using the removable soil samples, or that the beam loss is not well described with more beam lost inside the aperture of the E7 dipole.

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[4] The front face of the dipole iron is used as a reference

[5] Using 7.5% as per the SBMS subject matter and a soil density of 1.8 g/cc. The concentration factor of 1.1 has not been included.

[6] This differences is larger than one would expect. Additional work should be conducted to understand the difference.

K. Yip has provided a new profile plot with the beam striking the upstream surface of Booster dipoles as shown in the figures of footnote 2. The contours follow the old technique for estimating where the boundary of soil activation concern is. K. Yip has also moved[7] the source upstream to the transition in the beam pipe that is at the six inch quadrupole. He obtained a similar result as hitting the magnet yoke face with a result of $1.26*10^{-6}$ n(E>20 MeV) per proton at the middle soil sample location and $1.7*10^{-7}$ n(E>20 MeV) per proton at the downstream soil sample.

A calculation was conducted using cylindrical symmetry for the Booster is a straight tunnel with a tunnel radius of 150cm. The magnet iron was approximated as 13 cm thick in one run and 25 cm thick in another. The results are shown in Figure I. The neutron fluence peak for 13 cm of iron is $1.6*10^{-6}$ n/cm^2 per proton in reasonable agreement[8] with the calculations conducted by K. Yip ($1.3*10^{-6}$). The results were run for 800 MeV protons and K. Yip used 1000 MeV. The draft of this report did not have the long tails in the forward direction. The sextapole and quadruple were found to have too large an internal diameter. With the correct internal diameter of these downstream elements an extended forward region of elevated fluencies is created and found in agreement with the calculation conducted with K. Yip. The comparison in the backward direction revealed that the quadrupole used in the model by K. Yip had an outside diameter that was too. Finally, to take into account the mass of the RF cavities the material of the cavities was added in the backward direction in the z-axis symmetry model. A view of the MCNPX model with symmetry is shown in figure II.

[7] K. Yip to D. Beavis e-mail, Sept. 10, 2014
[8] When the difference for distance in the two model geometries is accounted for the comparison is $1.4*10^{-6}$ verses $1.3*10^{-6}$.

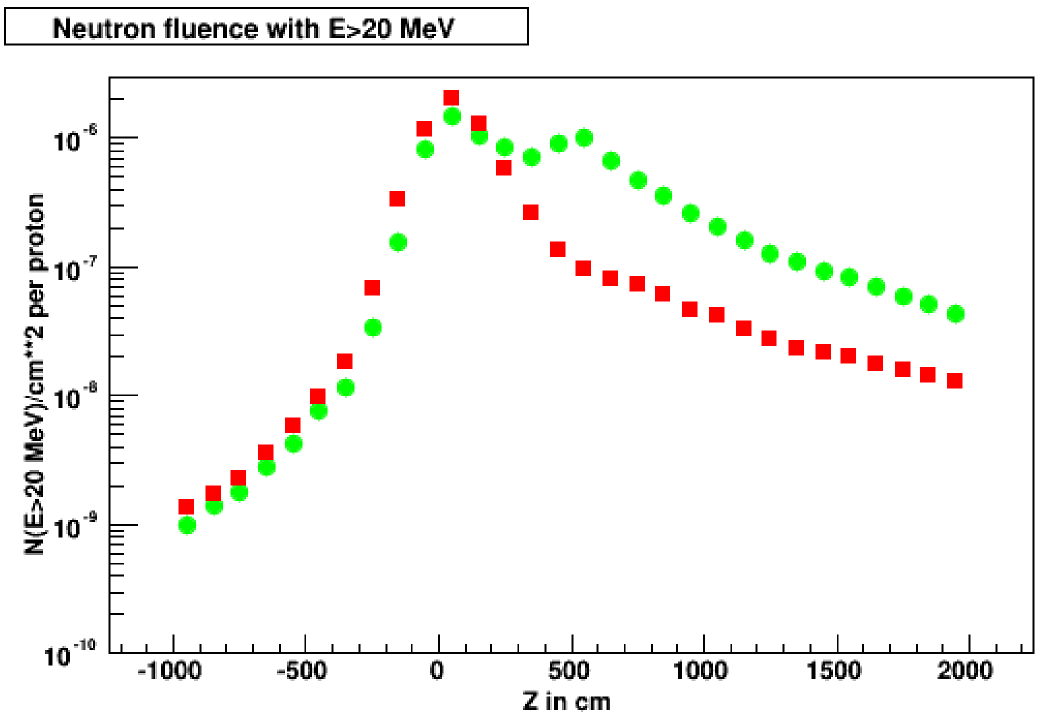

Figure I: The green circles are for a dipole with iron 13 cm thick and the red squares are for the dipole iron 25 cm thick. The internal radii are different. The bump in the green circles at 5 meters is caused by the radiation that does not strike shielding inside E7 and then strikes the sextapole and quadrupole. The neutron fluences are tallied at a depth of 10 cm into the soil for a tunnel with a radius of 150 cm.

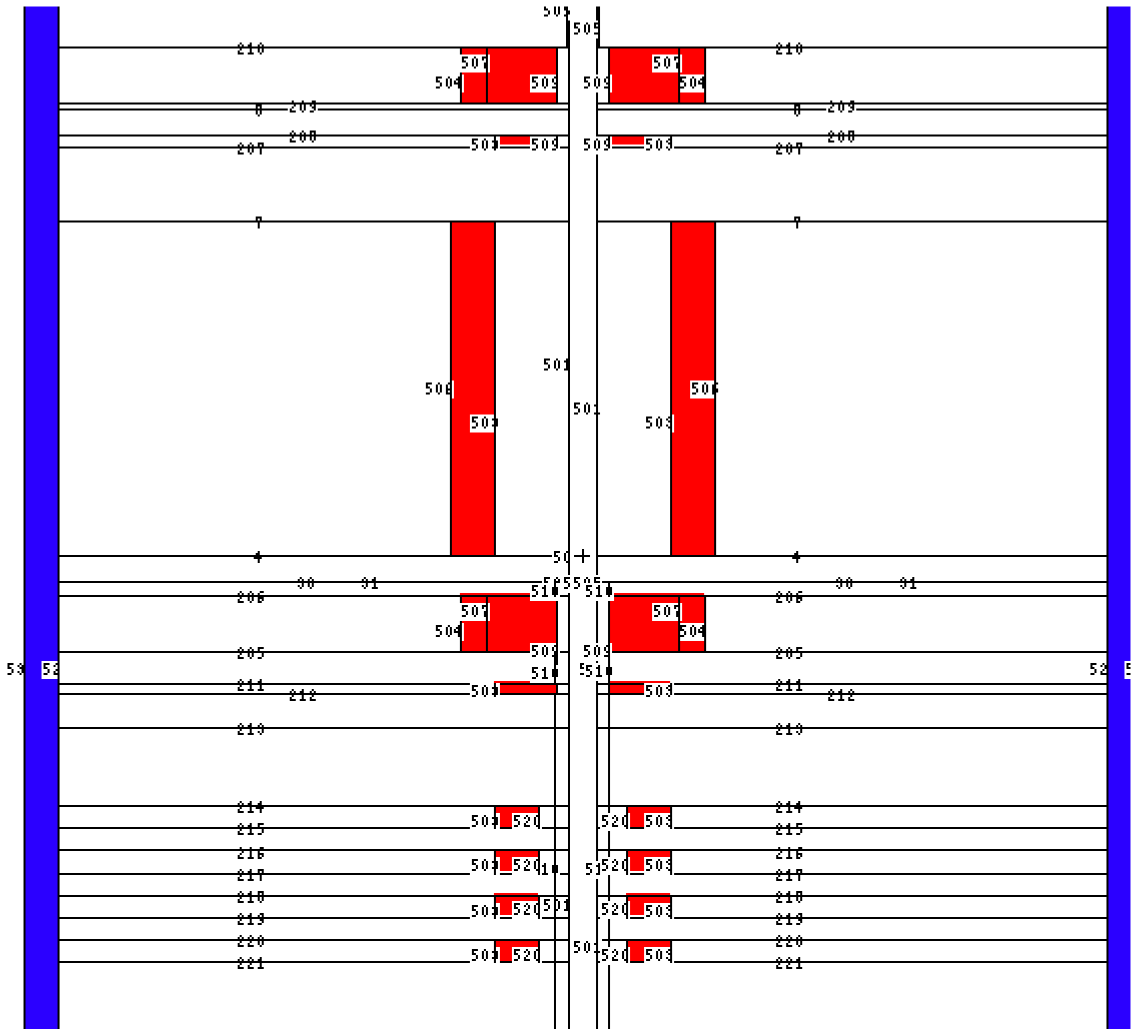

Figure II: Azimuthal symmetric model of the booster E7 area. The blue sides are the dirt tunnel, the sextapoles, quadrupoles, RF cavity, and the dipole are modeled. This is a plane view at beam height.

The results have an initial peak at about 1 meter downstream of the front face of the E7 dipole. The green points use a geometry that is a slice at the mid-plane. The second peak at 500-600 cm is from the radiation striking the sextapole and quadrupole downstream the E7 dipole. The red squares are for a geometry that more closely approximates the vertical slide through the system. The downstream magnets are now shadowed by the dipole pole tips. The long forward tail starts at about this location. Additional forward elements are not included in the model. Neutron trajectories created at zero degrees at the front of the E7 dipole would strike the quadrupole and essentially miss the E8 dipole towards the outside of the ring. In the backward direction the results depend only slightly on how the E7 dipole is modeled. The green points should be used to estimate the cap dimensions.

Steel or light concrete was added to the model in the vicinity of the front end of E8. It was determined that it would take substantial shielding to reduce the radiation sufficiently to make it worth the effort for the cap length. It was expected that adding the shielding would hamper access to equipment and most likely not be worthwhile.

To estimate the size of the cap with the proposed method the effective column height must be known. The effective column height is the length in centimeters that the number density of the radio nuclide of interest at y=0 (N) would be multiplied by to get the total number of atoms in a vertical soil column. I have assumed that the source is centered in a circular tunnel. The number of radioactive atoms in a vertical column at position x and y can be calculated and is proportional to the integral of N(xo,yo,zo)* exp(-d/AL)/(Rt*Rt) where d is the distance through soil (cm) (d=Rt-150) , AL is the attenuation length in cm of the neutrons above the appropriate energy and Rt is the transverse radius in cm (Rt=sqrt(x^2+y^2)). It is simple to get a numerical integration to an accuracy of a few percent using a spreadsheet. The results are shown in Table II. The numbers can be substantially larger than the 60 cm used in the SBMS exhibit for positions on the side of the tunnel. The large change at 160cm is the result that the water cannot leach out the vertical column under the tunnel so only y>0 is used if the distance is less than the tunnel radius.

Table II: Effective Column Height for a 150cm Radius Tunnel

Distance from centerline (cm)	Effective column height (cm)
0	36
40	37
120	49
140	61
160	207
210	245
260	279
310	309
360	337
410	363
460	387
510	410
560	431
610	452
660	472

Now that the distributions from two different calculations are reasonably understood the impact on the soil cap dimensions can be determined. **Based on the exhibit in the SBMS and the technique used by K. Yip, which came from the previous SBMS exhibit, the cap should extend to shadow a neutron fluence of 5.8*10^{-9} n(E>20 MeV) per cm^2 per proton.** The tritium production threshold is approximately 25 MeV fwhile the ^{22}Na production threshold is approximately 50 MeV. Using the technique that I have proposed then the tunnel[9] one needs to cap to a neutron fluence[10] :

Leff*Flux(E>25 MeV) = 1000pCi*(1055) for tritium,
and
Leff*Flux(E>25 MeV) = 100pCi*(2841)/0.8 for ^{22}Na.

The sodium 22 concentration establishes the size of the cap. The factor of 0.8 for sodium 22 is the ratio of neutrons above 50 MeV to the neutrons above 25 MeV evaluated in the peak region. This ratio tends to decrease in the backward direction and can increase in the forward direction. The edges of the tunnel at the extremes have an Leff of 207cm and requires that the **z-range for the cap is determined at a neutron fluence of 1.7*10^{-9} n/cm^{2}.** Based on Figure I and allowing for a 10 degree vertical angle results in the **start of the cap 9.5 meters upstream of the front face of the E7 dipole.** The downstream end would require the cap to extend until the inside of the tunnel shields the outside wall as suggested by K. Yip and also used in the Booster dump cap design.

The contours provided by K. Yip can be used with an attenuation factor to adjust for changing the parameters of the calculation. Figure III shows the neutron fluence for the model with symmetry about the z-axis and 13.3 cm of side iron. The points are for locations along the tunnel. The black line is the function exp(-d/60cm)/(Rt*Rt) where Rt is the transverse distance in cm from the tunnel axis, d is the thickness of soil in cm. The curve describes that data well. Extension beyond the points displayed can be done using the function or just extending the data with a straight line. At the extreme ranges of the longitudinal direction, especially backwards, there can be an initial large decrease.

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[9] The top could be capped to a higher value due to the shorter effective column height but this does not seem practical, but if need can be used.
[10] The numbers have been adjusted to use neutrons with energy greater than 25 MeV.

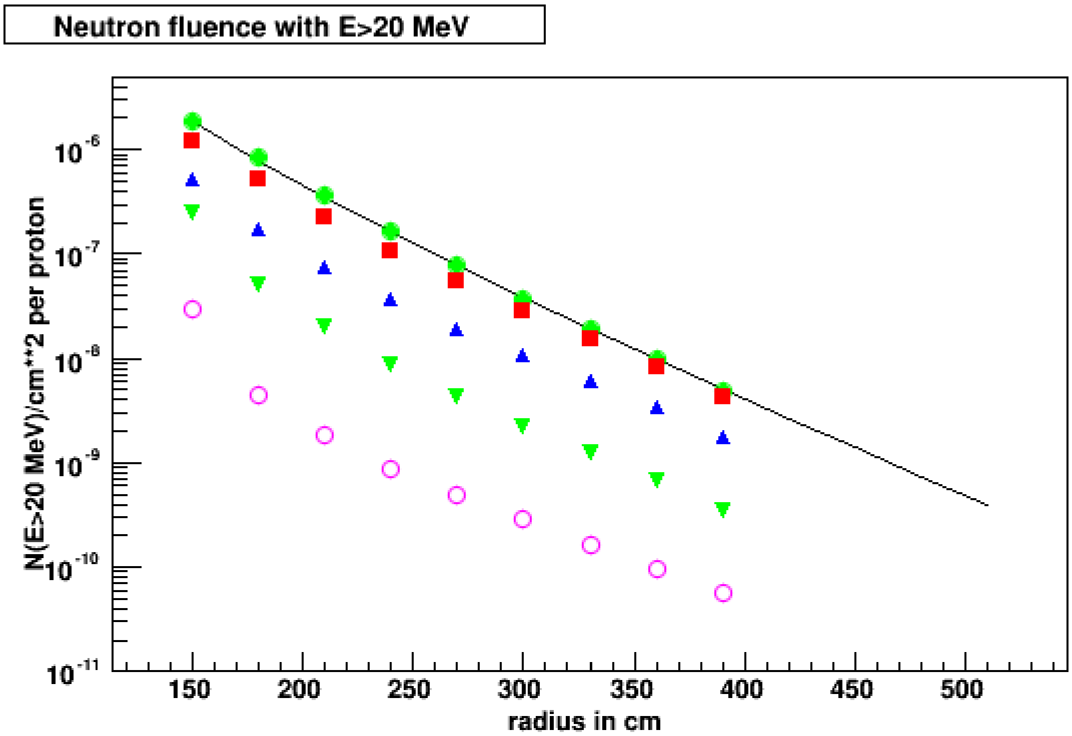

Figure III: The neutron fluences as a function of radius for the 150cm radius tunnel. The points are for different sections along the tunnel. The solid green are for 0<z<100cm with the front of E7 at z=0. The others are for 400-500cm, 800-900cm, 1200-1300cm, and -400 to -300 cm. The solid black line is a curve for exp(-d/60cm)/(Rt*Rt) with d being the thickness of soil.

A combination of the figures and tables presented here and the contours provided by K. Yip were used to determine the width of the cap. One meter has been added to each end of the cap to provide for the 10 degree vertical shift in water infiltration assuming that the mid-plane is 20 feet below the berm surface. In some locations this can be decreased as the slope of the berm will decrease the 1 meter margin. The dimensions are given relative to the center of the Booster tunnel. The inside of the cap should cover the tunnel to the inside to the d/s end of the F2 dipole. The cap can then start crossing the tunnel to intersect the corner of the outside intersection of the tunnel and building 914. It should then follow the building 914 until it provides a cover of 350 cm.

Table III: Booster E7 Cap Dimensions are given for the Outside of the Ring and the Inside

Z (cm)	Width on outside (cm)	Width on inside (cm)
-650	280	280
-350.	340	340
50.	570	570
450.	520	520
850.	520	440
1250.	450	370
1450.	450	320
d/s end of F2	405	150
u/s end of F4	350	100

The start of the cap would be 9.5 meters upstream of the E7 dipole. The downstream end will extend at approximately 1.5 meters past beyond the tunnel sections that have direct line of sight to the loss point.